Polarized RF Guns: Problems and Prospects

Accelerator Physics and Technology Seminar

Fermilab

September 23rd, 2004

Outline

- Motivation
- Conventional Polarized Guns
- Problems related with the required Cathode Material
- R&D at Fermilab
- Summary

Motivation

- RF Guns provide high accelerating fields and voltages
- Thus they are a premier choice for high brightness electron injectors
  - DC guns deliver the gradient but lack the voltage (typically a few hundred keV compared to a few MeV in RF guns)
  - Pulsed DC guns may deliver similar performance
  - DC/RF hybrid guns seem particularly interesting
- A RF gun will be even more attractive for certain applications if it delivers spin-polarized beams

Motivation

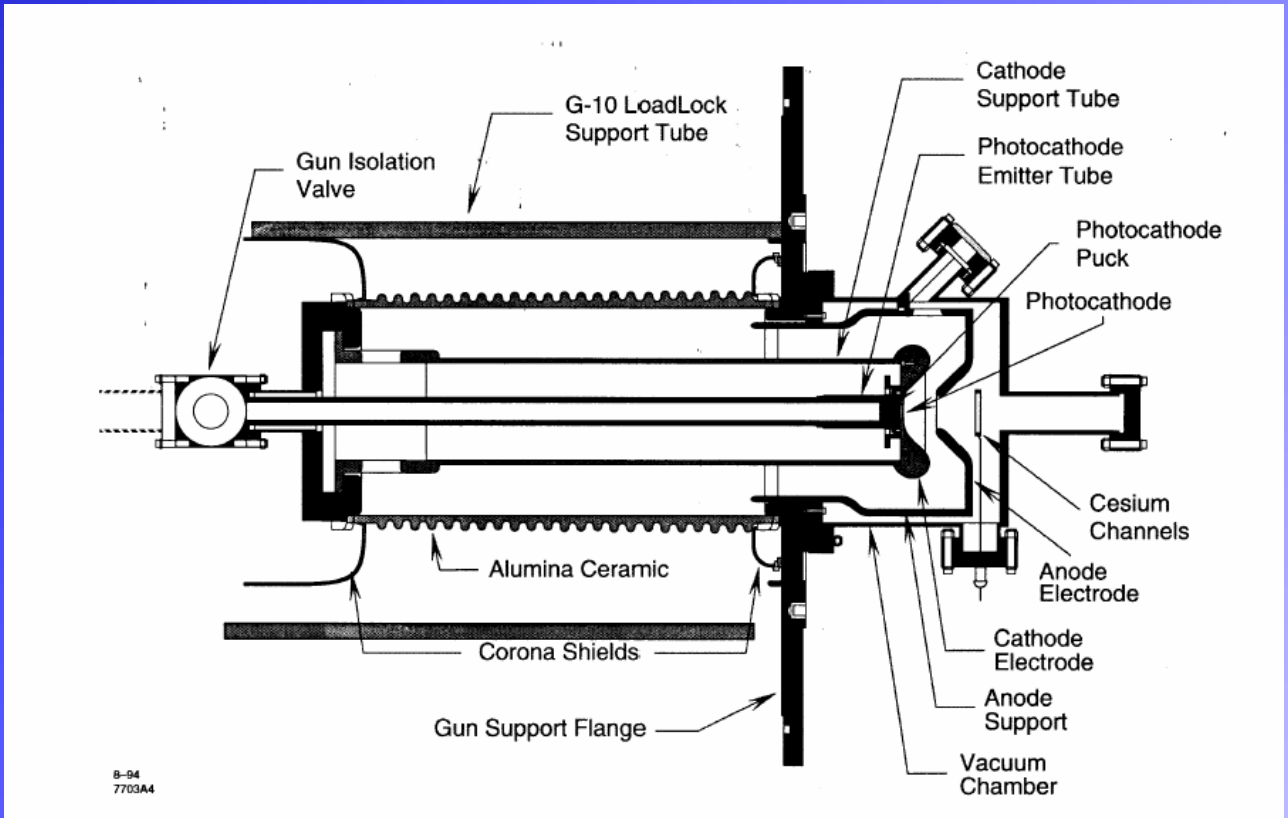
- In the A0 Photoinjector we study high brightness beams created in an RF gun
- One special focus of recent work is the creation of flat beams
- Although it is a far stretch in the moment, we hope that this development may at one time be used in a linear collider

BUT:

For that the Photoinjector would have to deliver polarized electrons

Conventional Polarized Guns

- For example the SLAC gun



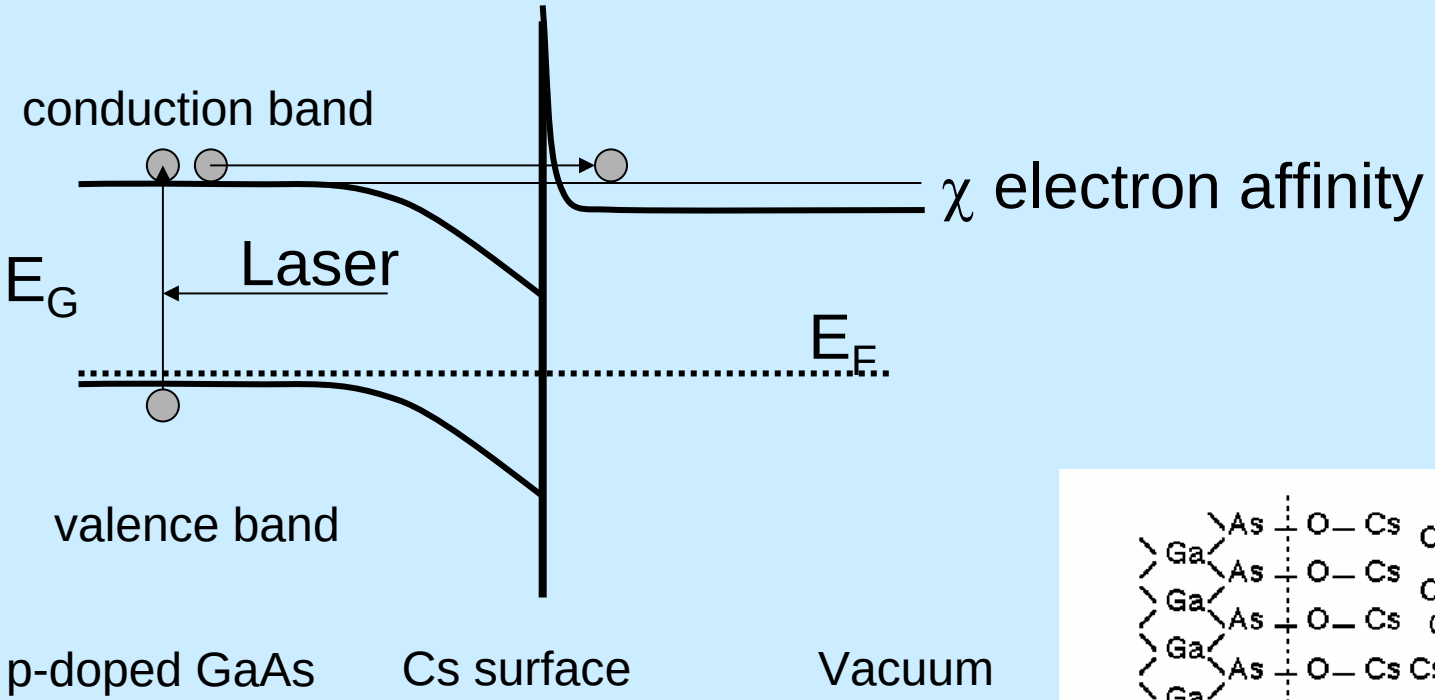
Clendenin et al, NIM A 365, 1-27

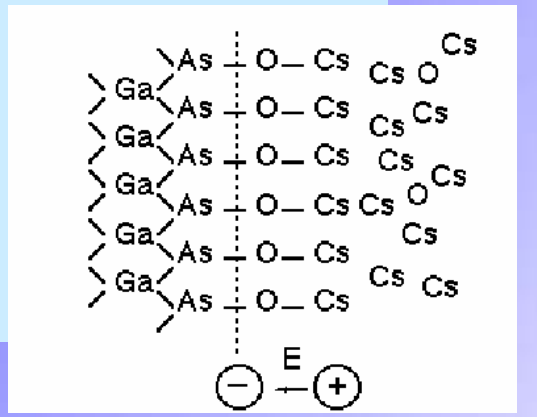
Conventional Polarized Guns

- DC gun with a voltage of 120 kV
- Surface field at the cathode of 7 MV/m
- Negative electron affinity (NEA) photocathode
- Illuminated by a YAG-Ti laser system
- Vacuum pressure 10^{-11} Torr with partial pressures of

  H_2 $1x10^{-11}$ Torr
  H_2O $2x10^{-13}$ Torr
  CO,N_2 $2x10^{-12}$ Torr
  O_2 $2x10^{-14}$ Torr
- Bunch length at cathode 2ns compressed down to a few tens of picoseconds

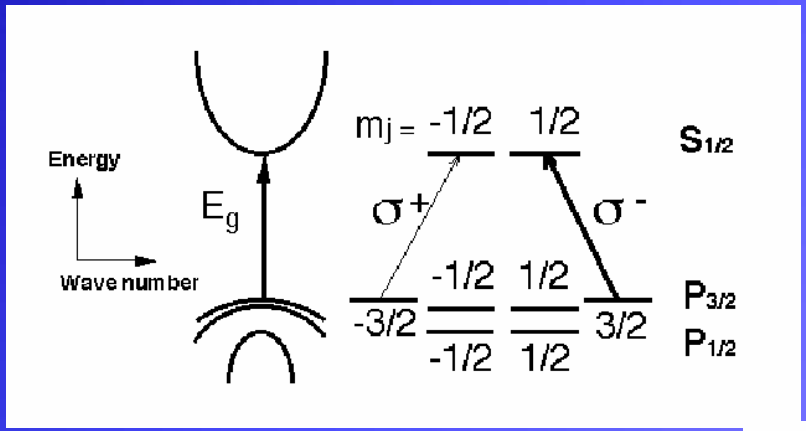
Negative Electron Affinity





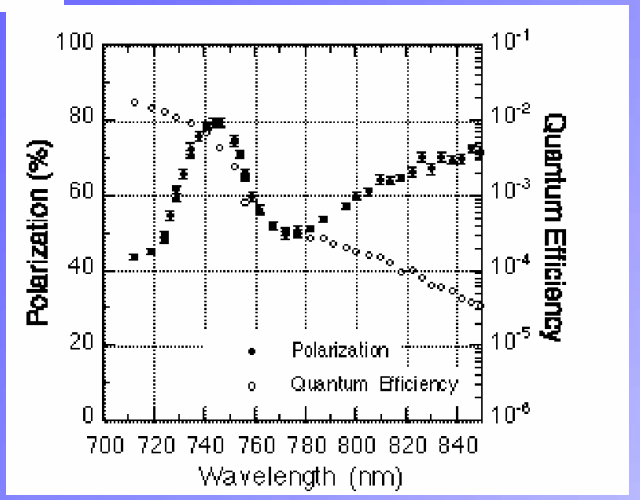
Contributions:	band gap	1.4 eV
	band bending	~0.9 eV
	Cs	~3.3 eV
Work Function:	bulk GaAs	5.5 eV

Polarization



Start off with a polarized laser
Increase polarization by straining the material
⇒removes degeneartion of energy levels

The strain can be achieved by growing GaAs on a substrate with slightly different lattice constant.
Remark: In the example on the right χ is 0.02 eV



Problems

The secret is in the monolayer of Cs and O on the surface.

That means the cathode is very susceptible to deterioation by

- chemical reactions with the residual gas,
- ion impact.

The cure is an extremely good vacuum (see above)

In RF guns there is the possibility of electrons hitting the cathode. In that case one has to worry about

- damage by electron impact
- dark current due to secondary electron emission (reports from Novosibirsk say they saw 100 times more dark current after activation)

The problems are the same regardless if it is strained or bulk GaAs

Ion Impact

- Ions are inevitably generated by the electron beam

Originally there are donors in the surface that bend the bands by ~0.9 eV

$$\varphi = \frac{eN_d^2}{2\varepsilon_r \varepsilon_0 N_a}$$

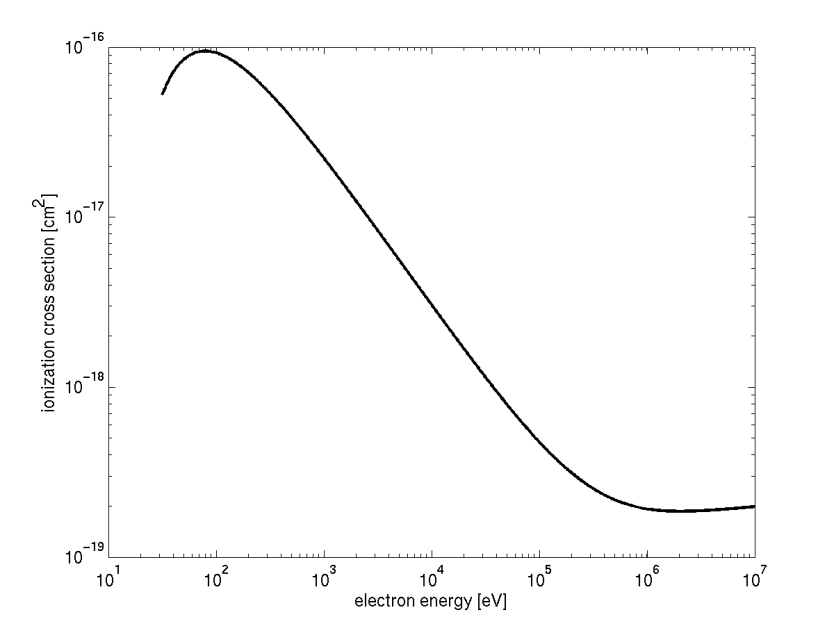
Assume the damage is done by effectively reducing the number of donors

$$\Delta N_d = \sqrt{\varepsilon_r \varepsilon_0 N_a \Delta\varphi / e_0}$$

which is approximately 10^{13} cm^{-2} ($N_A=10^{19}$ cm^{-3}, $\Delta\varphi=0.02$ V), (compare: There are $6\cdot10^{14}$ cm^{-2} atoms on the surface layer)

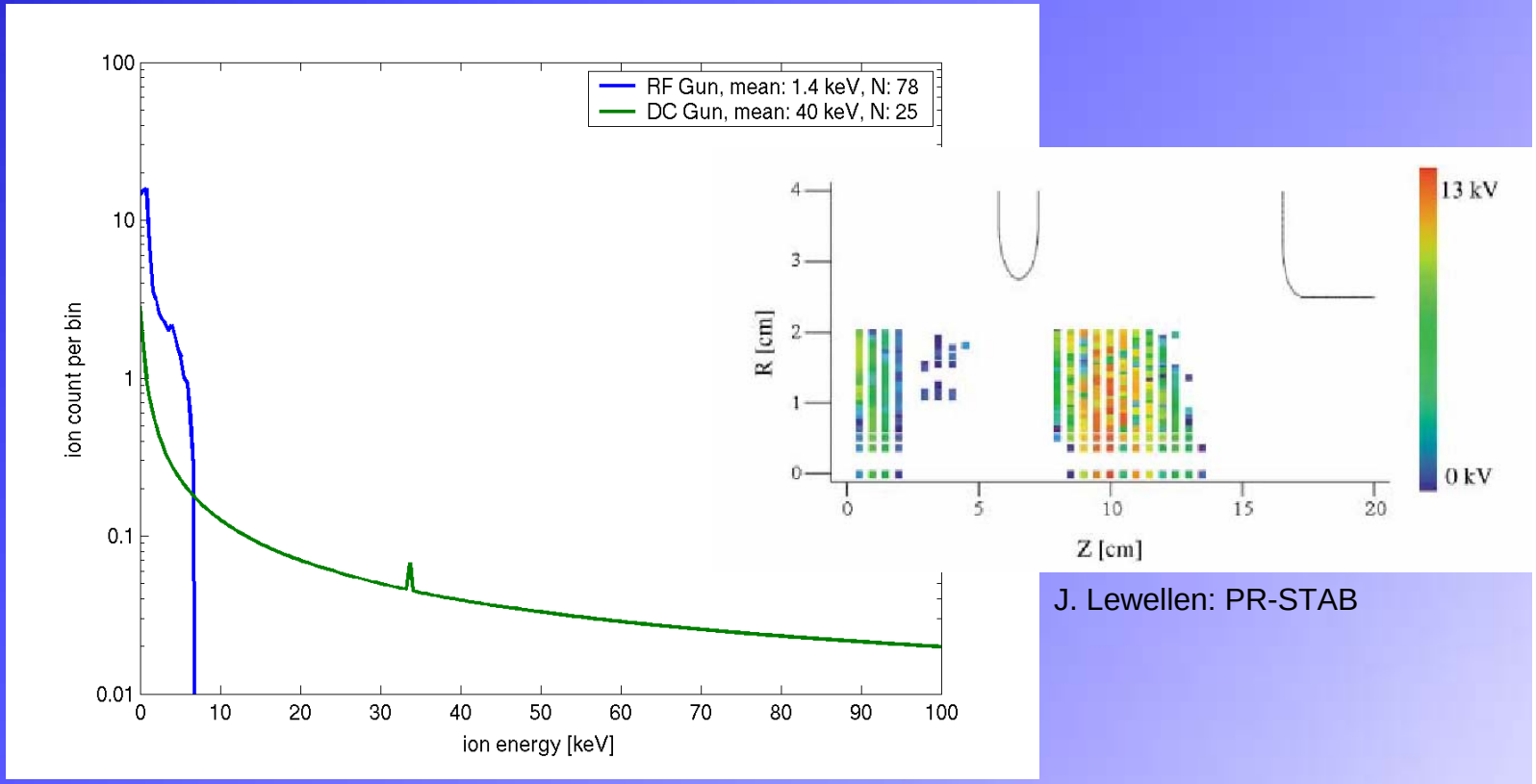
Ion Impact

- Residual gas is ionized by the beam along its path
- Dominated by H_2
- Energy dependent



Ion Impact

- Impact energies of H_2^+ in DC gun and RF gun



J. Lewellen: PR-STAB

Ion Impact

- The penetration depth of H_2 ions is ≤1Å in all cases (lattice constant of GaAs: 5.6 Å)
- All the damage is done to the surface
- Heat of adsorption for Cs on GaAs ≈2.6 eV max

	RF Gun	DC Gun
energy deposition Cs boiled off	109 MeV per pulse 4.2×10^4	1 GeV per pulse 3.8×10^5
time to loose 10^{13}	11000h	1200h

Ways to a usable Gun

- Improve Vacuum Pressure
  - the “standard” A0 gun has a pressure of 10^{-9} Torr
  - A GaAs cathode requires 10^{-11} Torr or better
- This takes care of the oxidation of the cathode surface
  - species to eliminate: O_2, H_2O, CO_2, CO, CH_4, ...
  - harmless: H_2
- This also takes care of ion bombardment, if the partial pressure of H_2 is improved

Idea

- Operate the gun at cryogenic temperatures to lower the equilibrium pressure
- Superconducting gun prevents the use of solenoids $\Rightarrow$ ruled out for flat beams (some people argue about that, but certainly this would be a much bigger project)
- Operate copper gun at liquid nitrogen temperature
- Gas desorption strongly depends on temperature:

$$\frac{dN}{dt} \propto N \exp\left(-\frac{E}{RT}\right)$$

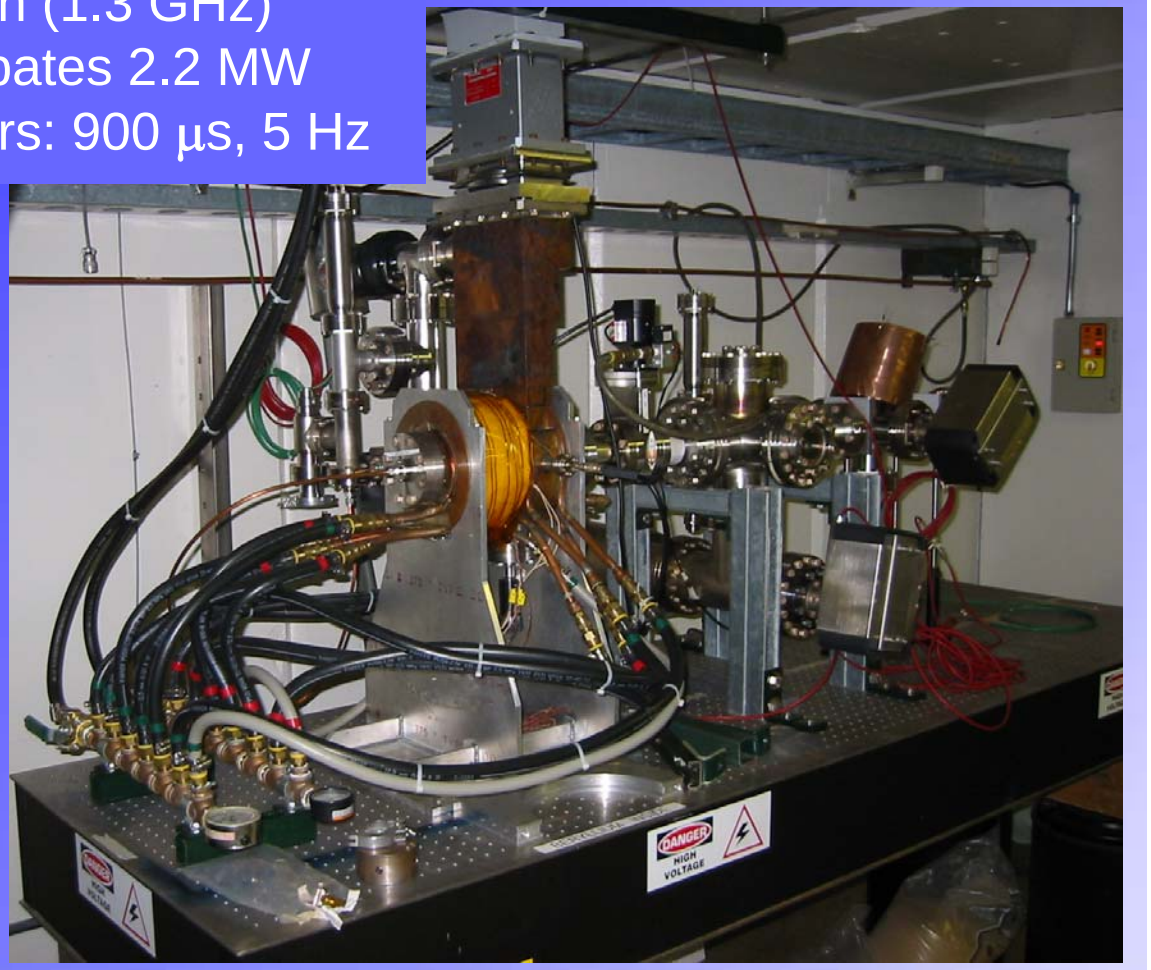
for E≈10kJ/mol (adsorption energy of CO) -> factor 10^5!

Earlier Attempts

- CLIC (1997)
  used GaAs in their S-Band gun, used green laser PEA cathode, which may avoid most of the problems
- Novosibirsk (1997/1998)
  had an S-Band test gun, saw a large amount of dark current, Q.E. lifetime 30 min with rf on (one attempt, in another paper they report only a few seconds), vacuum pressure 10^{-10} Torr
- SLAC (present)
  SBIR with Duly Research, S-Band Plane Wave Transformer (PWT), no results yet. They hope to improve pumping by the more open structure of the PWT

Prototype Gun

- Prototype gun available at Fermilab:
  ->1.6 cell L-band gun (1.3 GHz)
  -> at 35 MV/m dissipates 2.2 MW
  -> TESLA parameters: 900 μs, 5 Hz



Prototype Gun

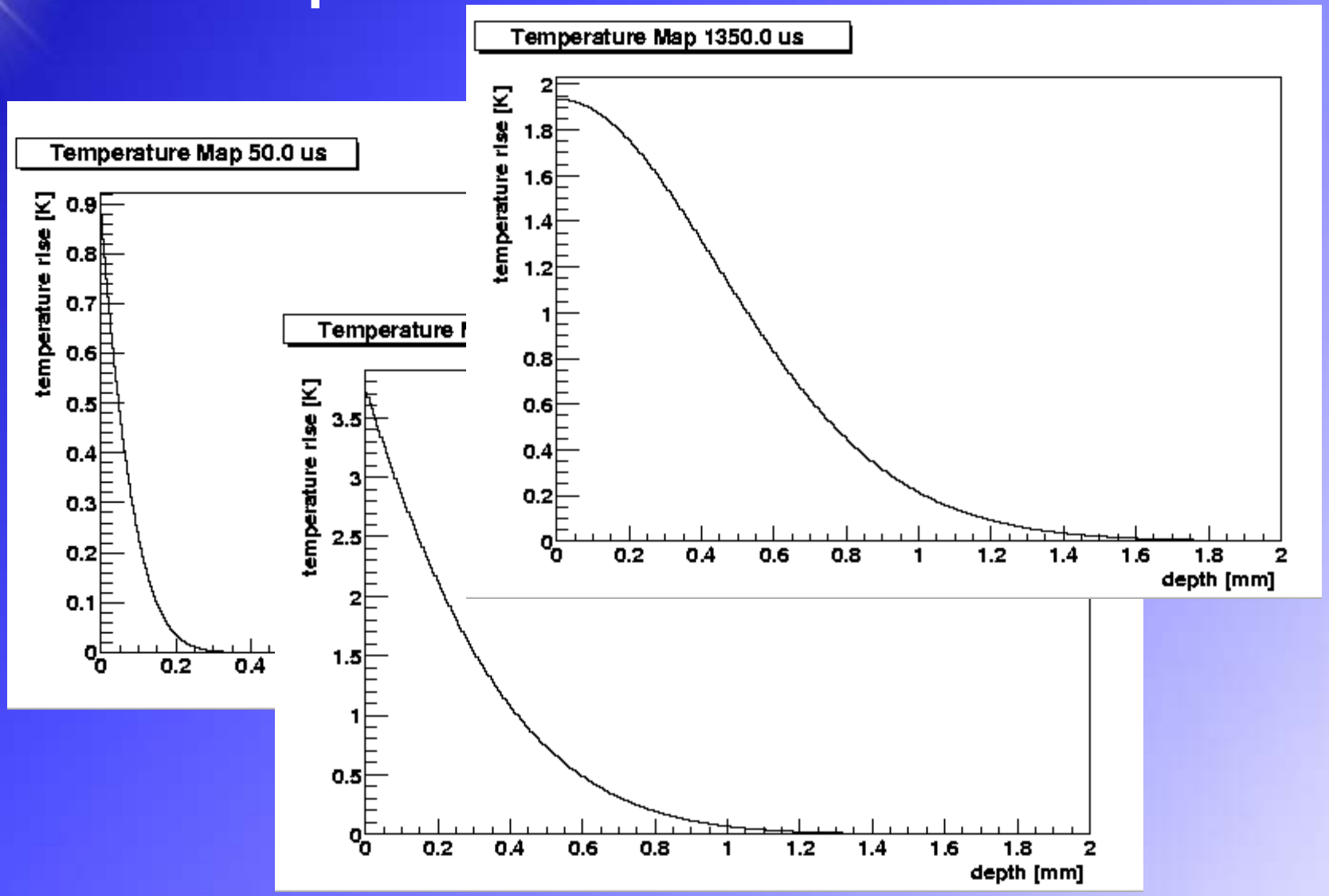
- At 80 K the dissipated power is reduced by a factor of 2.8
  -> 780 kW peak power
  -> 3.5 kW average power
  -> Heat flux at cooling pipes 2.5 W/cm^2
  (nucleate boiling limit 15 W/cm^2)
  maximum in iris with 3.1 W/cm^2

Temperature Distribution

- Surface Temperature rises with

$$T = I\sqrt{\frac{4t}{\pi\rho c\lambda}}$$

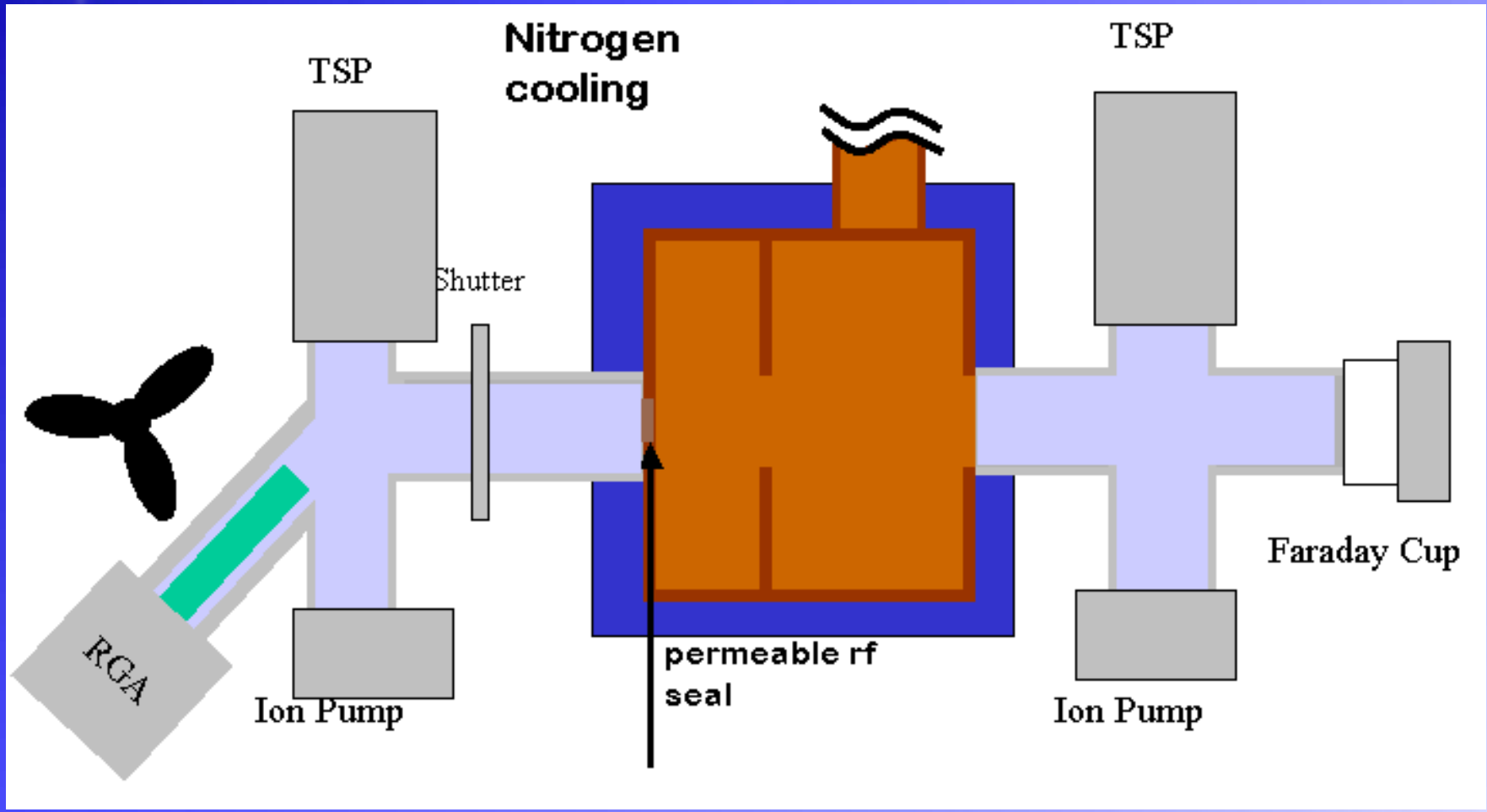
Temperature Distribution



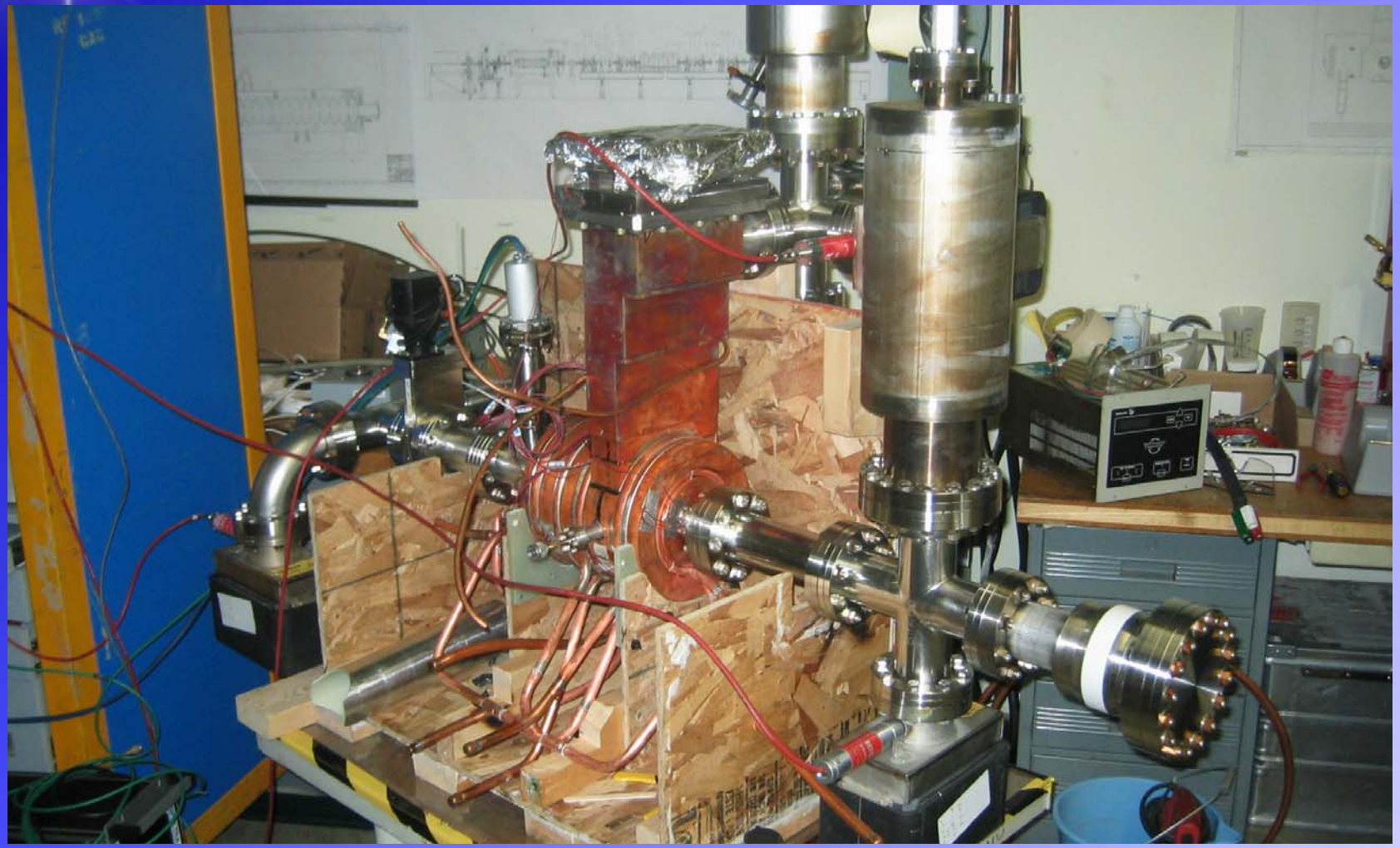
Phase I: Vacuum Tests

- Cool down to 80 K
  -> measure pressure, RGA
- Apply RF
  -> measure pressure, RGA
  -> measure dark current

Phase I: Vacuum tests



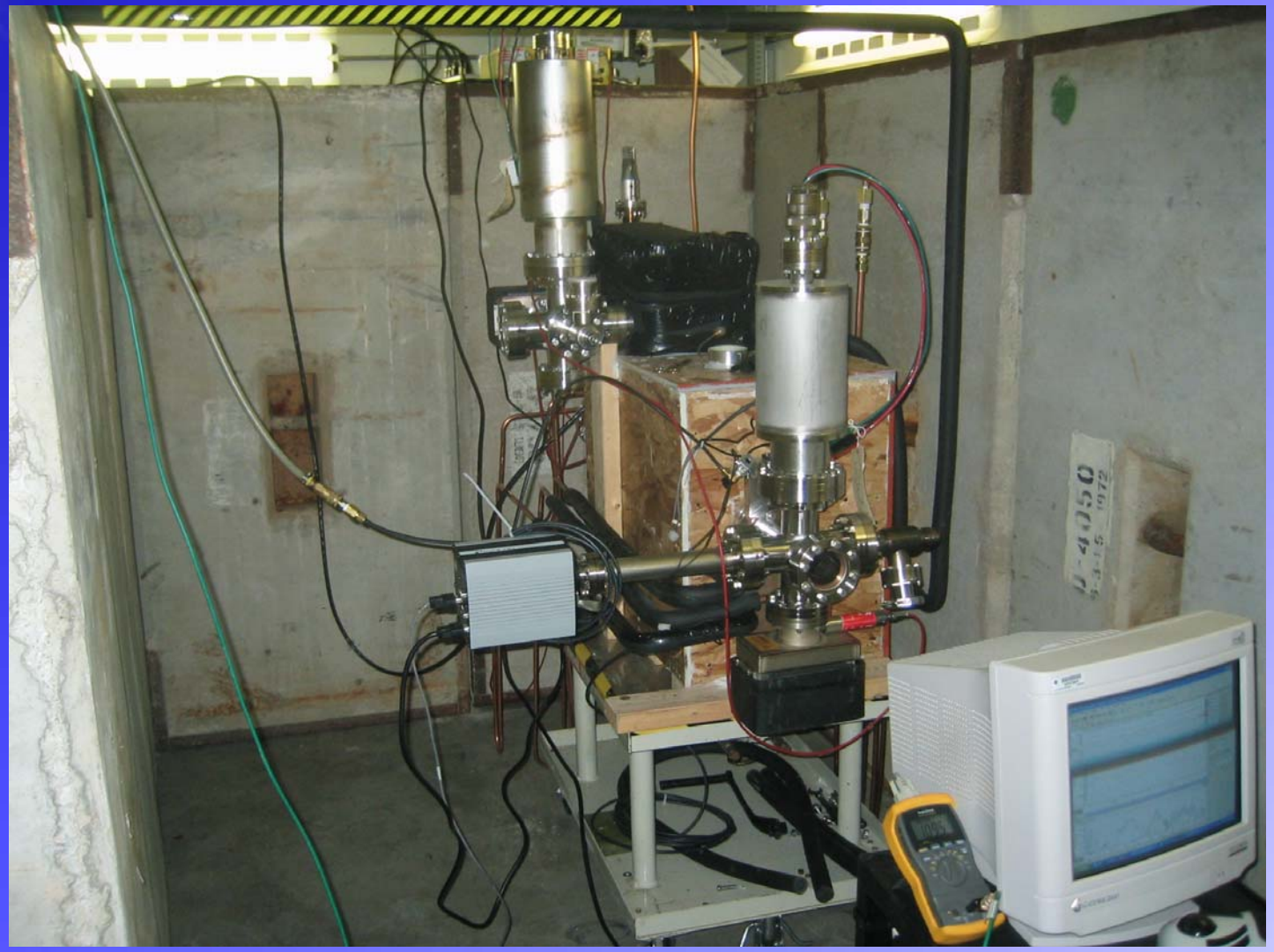
Phase I: Vacuum Tests



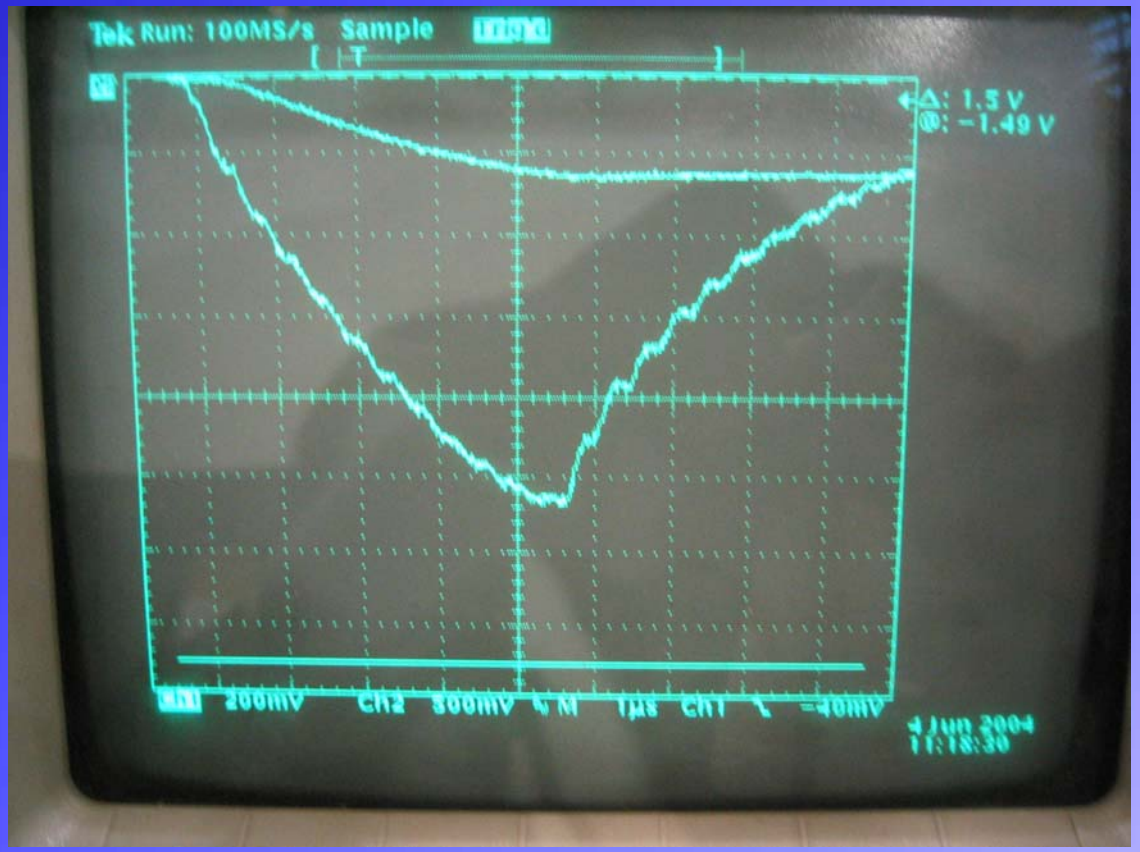
Phase I: Vacuum Tests

- Gun was disassembled and cleaned with Citrinox (standard procedure)
- After reassembly the gun was baked at 130°C for 24h
- Limiting device: Viton sealed gate valve
- If that is removed the next limiting device is the RGA with a bake-out temperature up to 250°C
- Cathode port left open for taking RGAs
  (This unfortunately leaves sharp edges where normally ther would be a flush surface)

Phase I: Vacuum Tests



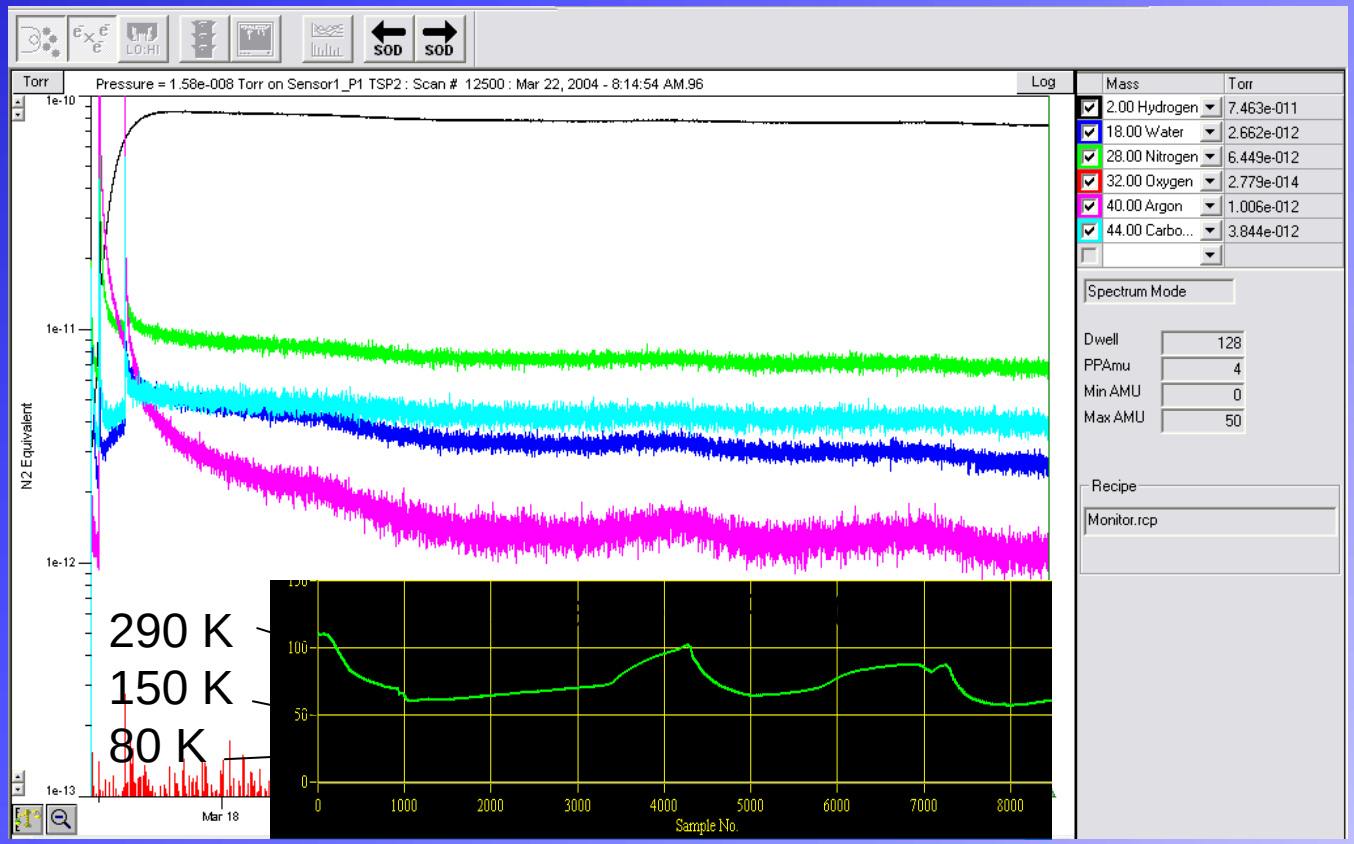
Apply RF



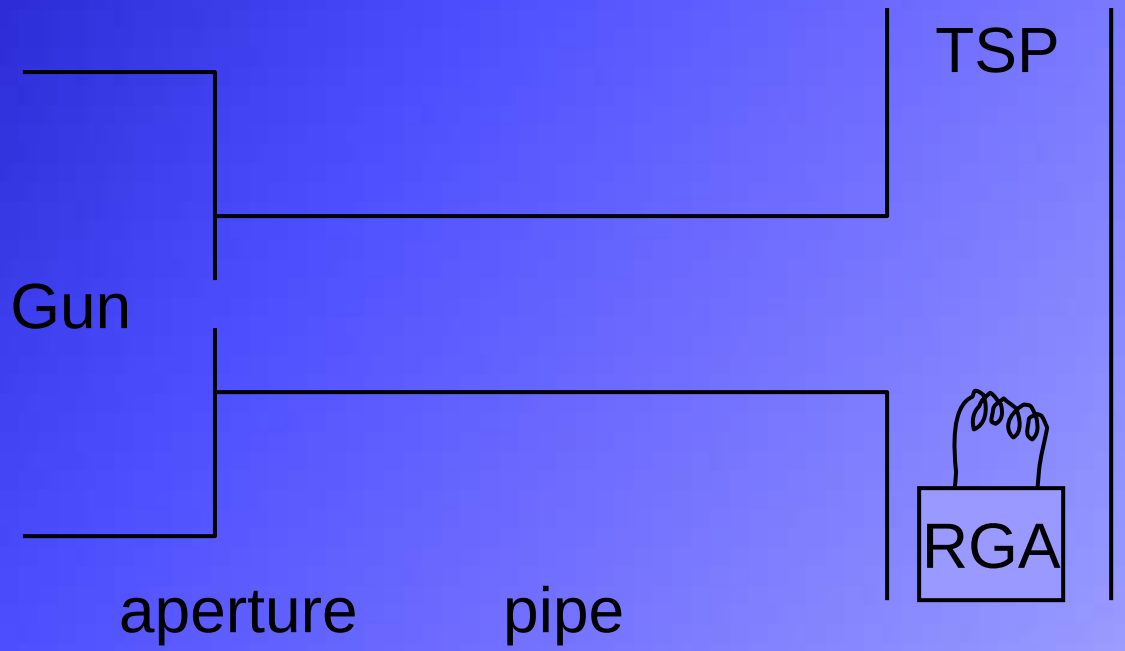
First RF pulse (5 μs, warm cavity, 1 MW)

First Cooldown

- Temperature and Pressure during Cooldown



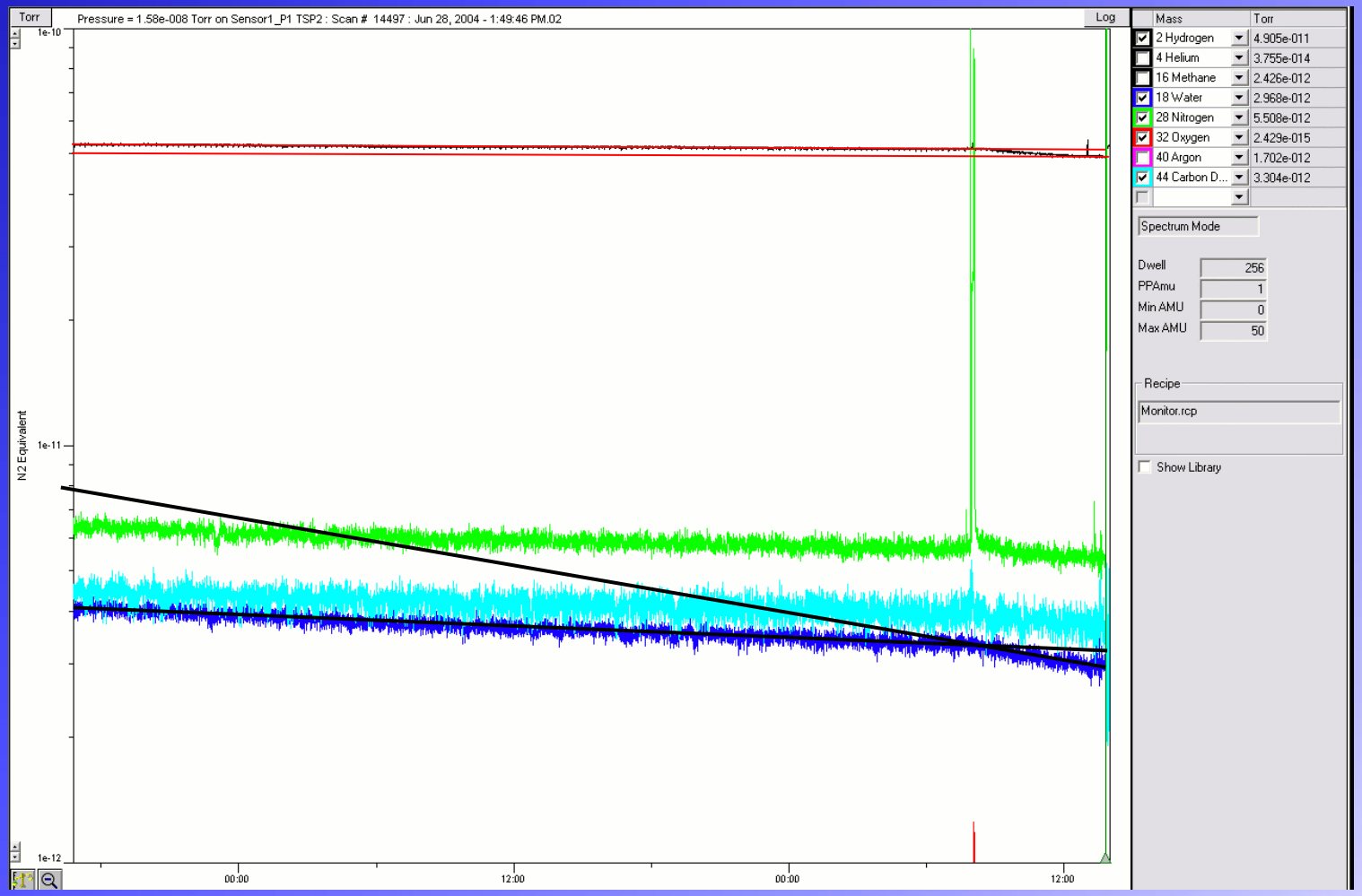
Vacuum Conductance



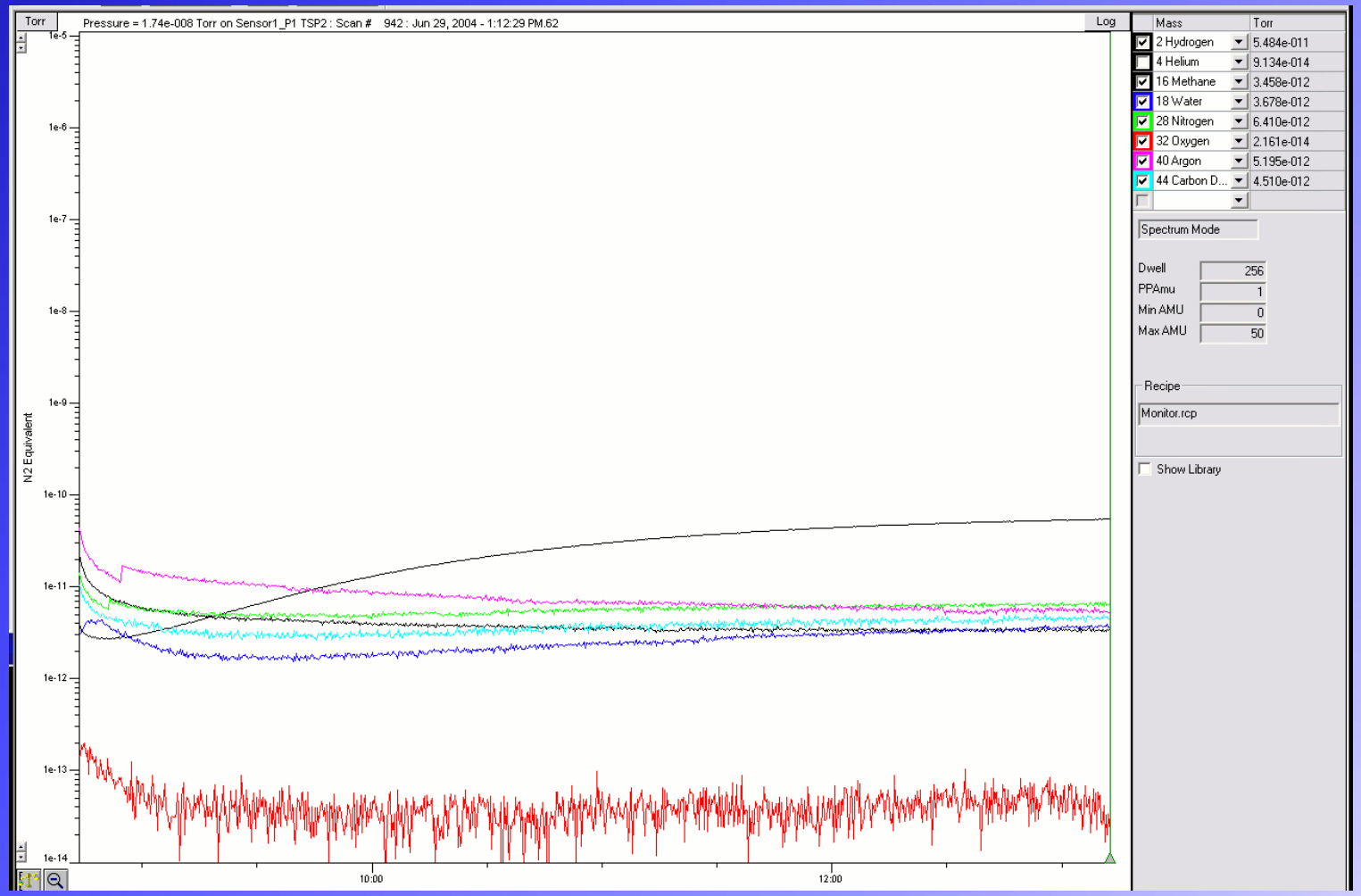
- aperture: $2.86*(T/M)^{1/2}\ D^2$ = 15 l/s (H_2O), 45 l/s (H_2)
- pipe: $3.81*(T/M)^{1/2}\ D^3/L$ = 55 l/s (H_2O), 165 l/s (H_2)
- total: $(1/C_1+1/C_2)^{-1}$ = 12 l/s (H_2O), 36 l/s (H_2)
- TSP (pipe to it): = 110 l/s (H_2O), 330 l/s (H_2)

the above holds at 80 K, at 300 K the numbers double

RGA during Cooldown



RGA with Valve closed

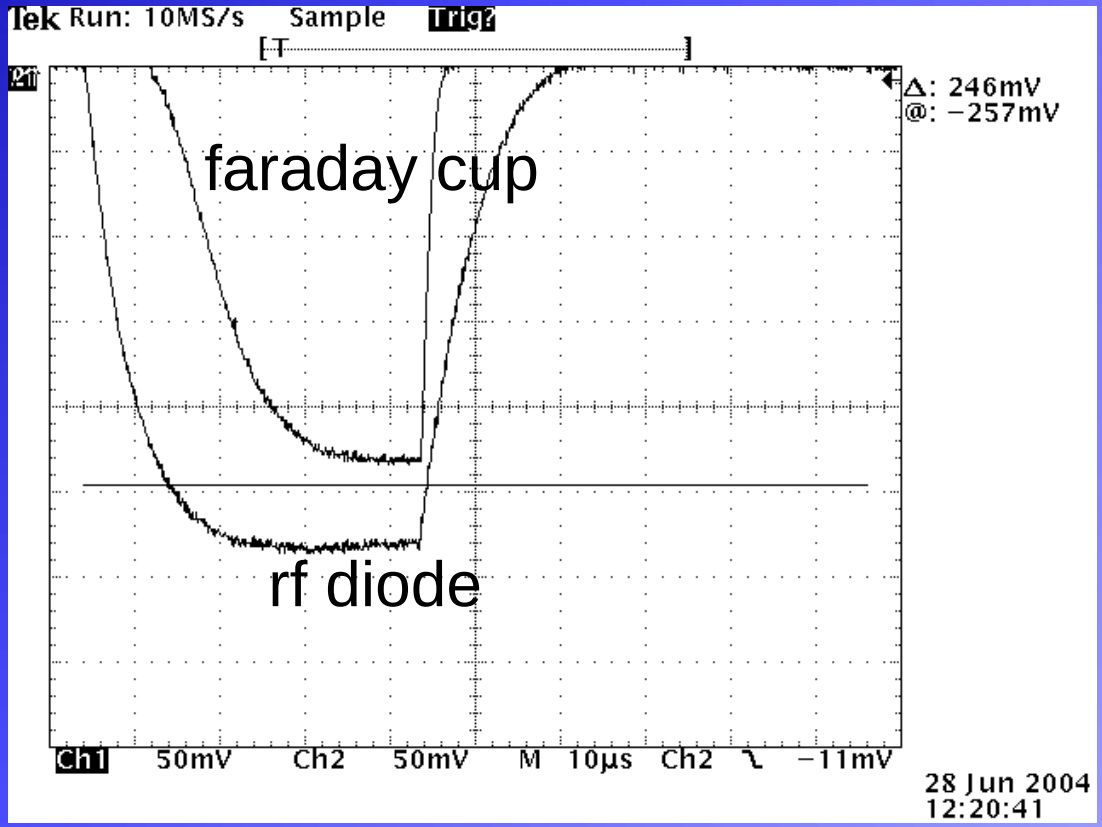


RGAs in Numbers

	valve closed	gun warm	gun cold
pressure H_2 pressure H_2O	$5.5\ 10^{-11}$ $3.7\ 10^{-12}$	$5.1\ 10^{-11}$ $3.4\ 10^{-12}$	$4.9\ 10^{-11}$ $3.0\ 10^{-12}$
pressure in the gun H_2 H_2O		 $1.4\ 10^{-11}$ $5.6\ 10^{-13}$	 $-8\ 10^{-12}$? $-6\ 10^{-12}$?

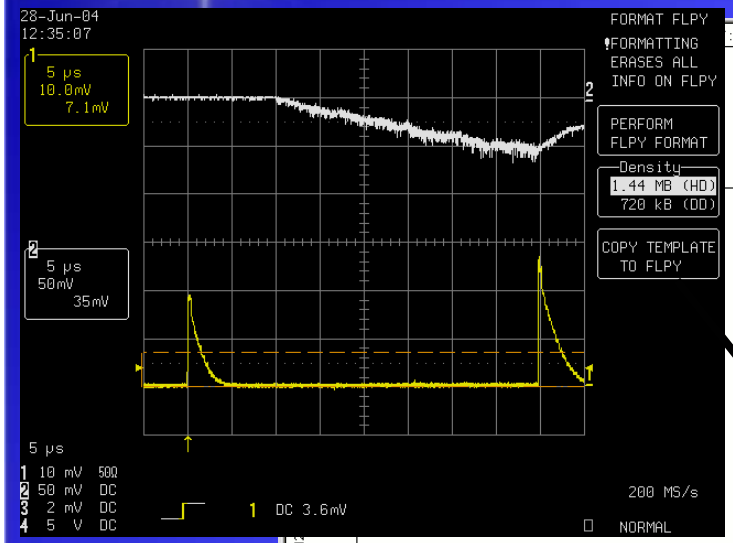
- The above table was created assuming there was a constant gas load in the RGA section
- Obviously there is a problem in this calculation (There is no anti-pressure!)
- An explanation may be a dirty gate valve and/or pumping by the outer surface of the gun

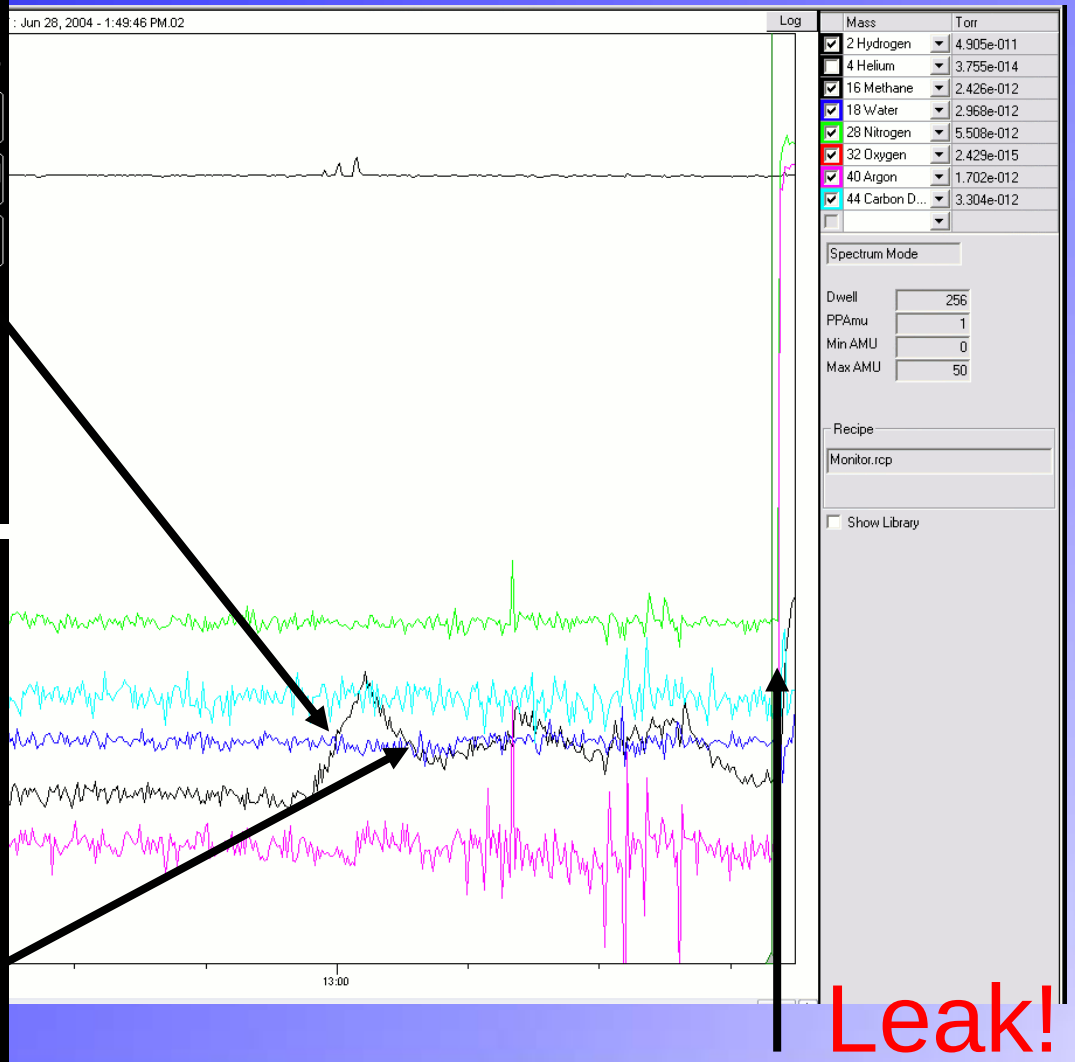
Apply RF to cold Cavity



RF pulse in the cold cavity: ≈29 MV/m, 40 μs, dark current level ≈1mA

RGA with RF running





Leak!

Phase II: Quantum Efficiency

- Built a cathode system
- Obtain a (set of) cathode(s)
- Laser diode for Q.E. measurements
- Cryostat
- Measure Q.E. lifetime, dark current

This will be part of an Phase I SBIR study in which Fermilab collaborates with AES (Advanced Energy Systems);

For that AES will provide the cathode chamber (built with C.Sinclair of Cornell as a consultant)

Phase III: Gun Design

- Design and construct a “usable” gun
  - This would be Phase II of the SBIR
  - look at various options besides cryogenic gun (PWT, hybrid DC/RF gun)
  - optimize for the required parameters
- Options for reduction of average rf power?
  - reduce heat load
  - reduce dark current

Just some Idea

The LEP cavities

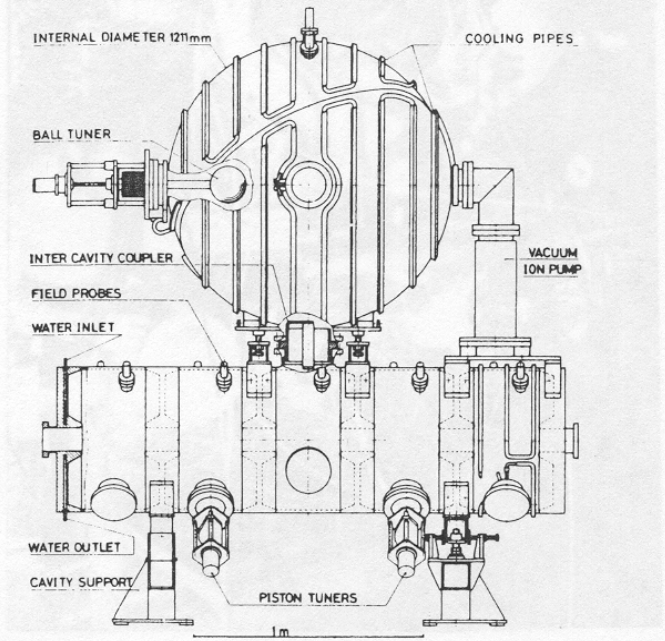


Fig. 5. Arrangement of coupled cavity system for LEP

IEEE Trans Nucl Sci NS-28, No 3 (1981)

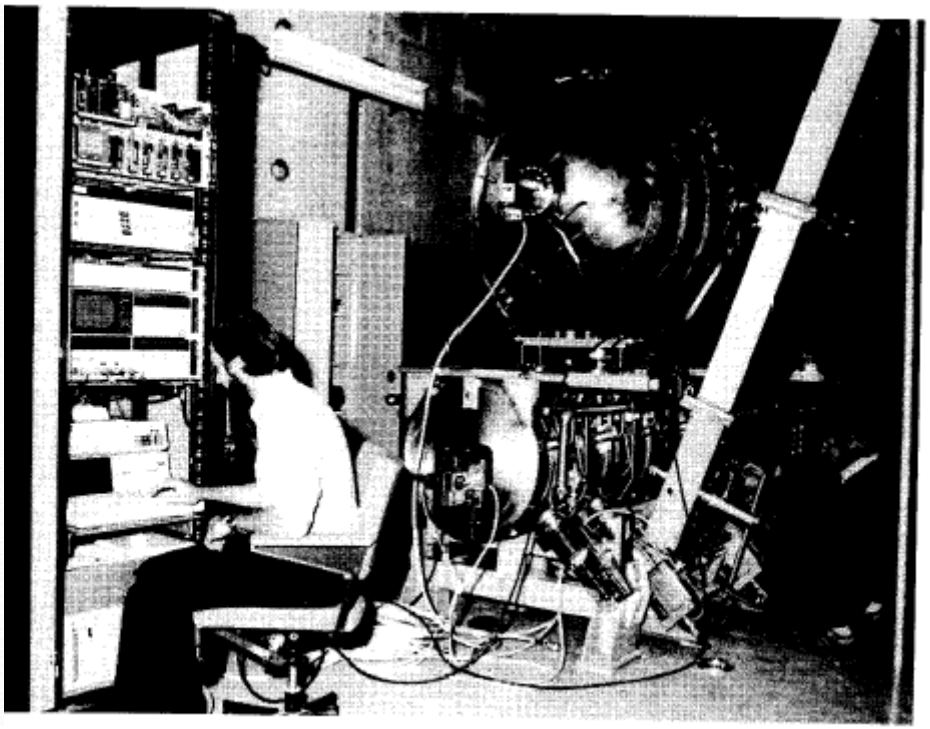
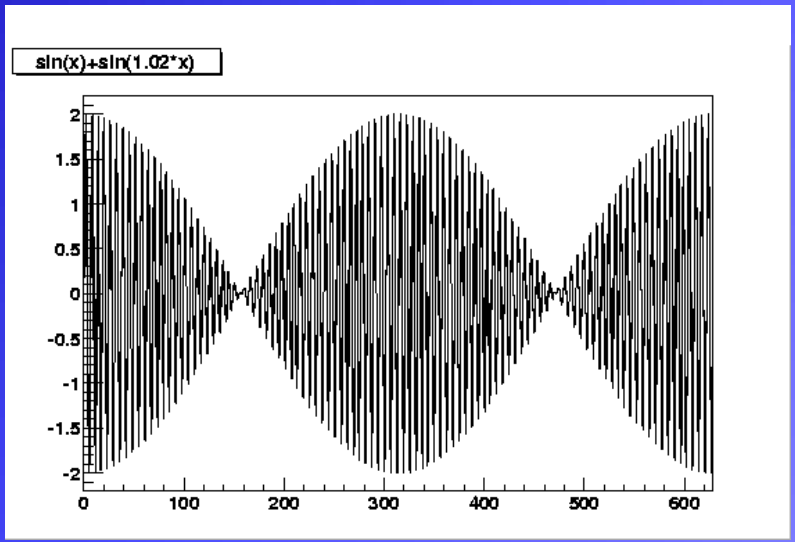


Fig. 7. Arrangement for coupler adjustments

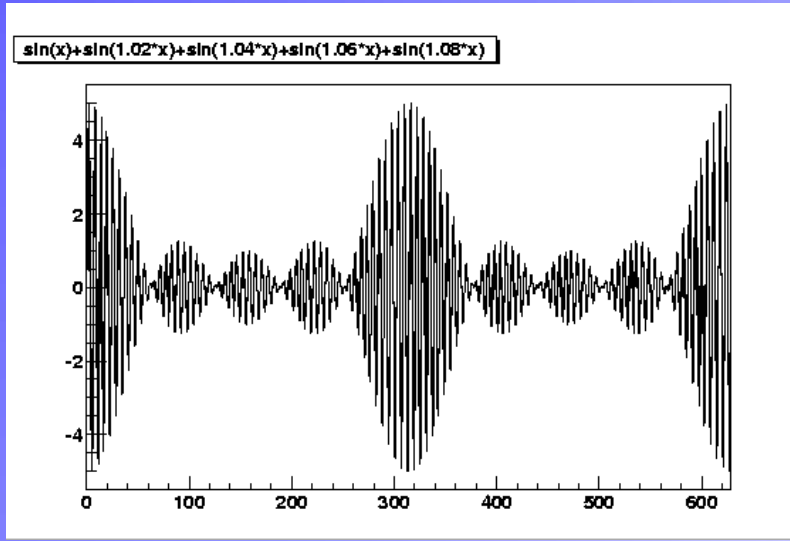
LEP Note 570

Some Idea cntd

- Coupled acceleration and storage cavity
- Reduce cryogenic load
- Reduce dark current



Or maybe have more than one?



Summary

- Polarized RF Guns are an appealing goal for somebody who works on sources for the linear collider
- Improvement of the vacuum pressure is a prerequisite for a successful attempt to build one
- A test stand has been established to do development towards a polarized RF gun at Fermilab
- Initial vacuum tests have been performed with promising yet not 100% conclusive results
- These tests will be continued by adding a cathode system to the apparatus

Thank You